Astrophysical Ages and Time Scales
ASP Conference Series, Vol. TBD, 2001
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The Oldest Stellar Populations at z $\sim$ 1.5

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Abstract. There are at least three reasons for being interested in galaxies at high redshifts that formed most of their stars quite quickly early in the history of the Universe: (1) the ages of their stellar populations can potentially place interesting constraints on cosmological parameters and on the epoch of the earliest major episodes of star formation, (2) their morphologies may provide important clues to the history and mechanisms of spheroid formation, and (3) they are likely to identify the regions of highest overdensity at a given redshift.

We describe a systematic search for galaxies at $z \sim 1.5$ having essentially pure old stellar populations, with little or no recent star formation. Our approach is to apply a "photometric sieve" to the fields of quasars near this redshift, looking for companion objects with the expected spectral-energy distributions. Follow-up observations on two of the fields having candidates discovered by this technique are described.

1. Introduction

One of the uncertainties in our picture of galaxy formation in the early Universe is in understanding how elliptical galaxies and the massive bulges of early-type spirals developed. The standard cold-dark-matter scenario implies bottom-up formation—small-mass systems form first, possibly as objects something like the ubiquitous star-forming dwarf galaxies found at lower redshifts; then these objects merge to form larger entities, including, in the denser regions, large spheroidal systems. However, there are at least two nagging worries regarding this scenario. Firstly, there is a correlation between color (*i.e.,* metallicity) and luminosity in elliptical galaxies (Bower, Lucey, & Ellis 1992; Ellis *et al.* 1996). As Peacock (1999) has observed, "It seems as if the stars in ellipticals were formed at a time when the depth of the potential well that they would eventually inhabit was already determined." Secondly, the very tight correlation found between stellar velocity dispersion in bulges and black-hole mass (Ferrarese & Merritt 2000; Gebhardt *et al.* 2000) seems to demonstrate an intimate connection between the formation of spheroids and the formation of supermassive black holes at their centers. It is certainly not obvious that this correlation could be produced from successive mergers of small building blocks, since supermassive black holes do not seem to be associated with pure disks or irregulars. In fact, both of these observations would appear to fit more comfortably with monolithic or quasi-monolithic collapse pictures of spheroidal formation; however, this statement is more a reflection of our current uncertainty than an endorsement of such models. What is clear is that direct observational constraints on formation mechanisms, environments, and formation epoch for spheroidals are necessary in attempting to sort out these difficulties.

2. The Earliest Major Episodes of Star Formation and Constraints on Cosmological Parameters

Figure 1 (*left*) shows the K' magnitude of L^* elliptical galaxies as a function of redshift, assuming only passive evolution of a solar metallicity stellar population formed essentially instantaneously at cosmic epochs of either 0.5 or 1.0 Gyr. At $z = 1.5$, such galaxies would have $K' \sim 19.5$, so they are quite easily detectable. Both we and others (*e.g.,* Dunlop 2000 and references therein) are finding galaxies about 1 mag brighter than this, presumably on the high-luminosity tail of the luminosity function and indicating that the stellar content of some early-type galaxies is essentially fully in place at very high redshifts.

If we could determine precise ages for old populations at high redshifts, we could potentially place interesting constraints on cosmological parameters as well as on formation epochs. This possibility is shown in Fig. 1 (*right*): if one could demonstrate an age of ≥ 4 Gyr at $z = 1.5$, with currently reasonable values of h_0 $(= H_0/100)$ and Ω_m all open models would be eliminated, and even Λ-dominated models with $z_f \sim 10$ are only barely consistent.

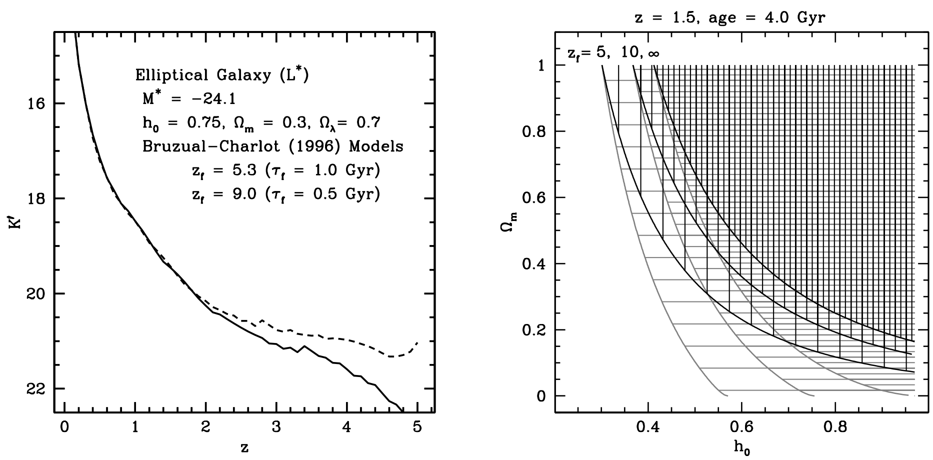

Figure 1. (*left panel*)—K' magnitude for a passively evolving L^* elliptical galaxy, assuming an instantaneous burst with formation redshifts of 5.3 (dotted line) or 9.0 (solid line). (*right panel*)—Constraints on the matter density parameter, Ω_m, and the Hubble parameter, h_0 $(= H_0/100)$ assuming the confirmation of a galaxy at $z = 1.5$ with a 4.0-Gyr-old stellar population. The hatched area to the right of each curve shows excluded regions, assuming star formation redshift z_f of 5, 10, and ∞, as indicated at the top. Gray curves are for open models $(\Omega_{total} = \Omega_m)$; black curves are for flat models $(\Omega_m + \Omega_\Lambda = 1)$. Even the latter require $z_f > 10$ to be consistent with $\Omega_m \sim 0.3$ and $h_0 \sim 0.7$.

3. Identifying Old Galaxies at High Redshifts

There have been three main approaches to identifying old galaxies at high redshifts: (1) looking for very red objects among weak radio sources (Dunlop *et al.* 1996, 2000; Spinrad *et al.* 1997), (2) wide-field multicolor photometric surveys (Thompson *et al.* 1999; Daddi *et al.* 2000), and (3) identifying red objects in radio source fields (this paper; see also Cimatti *et al.* 1997). We have been examining fields of radio-loud QSOs with $1.4 < z < 1.78$. We use a "photometric sieve" approach, which gives us high observing efficiency and clearly distinguishes objects with old stellar populations and little reddening from heavily reddened objects. Using the NASA Infrared Telescope Facility, we first image the fields of interest in the K' band, looking for objects with $18 \leq K' \leq 19.5$ within a $30''$ radius of the quasar. For fields with such objects, we then obtain J-band imaging, looking for objects with $J - K' \sim 2$. At this point we have eliminated typically 80% of our original fields; for the remainder, we must now obtain CCD imaging on the short side of the 4000 Å break, which occurs between the I and J bands for this redshift range. We usually try to obtain at least R and I photometry, although we have used a variety of standard and non-standard bands. Recently, a similar approach has been proposed by Pozzetti & Mannucci (2000). Of the 208 fields in our sample, we have at least some observations for about 60%; we have eliminated 74 fields as having no further interest, and we have 7 fields with quite firm old-galaxy candidates. It is significant that 5 of these 7 have more than one good candidate, including one field with 3. Spectral-energy distributions for some of these objects are shown in Fig. 2.

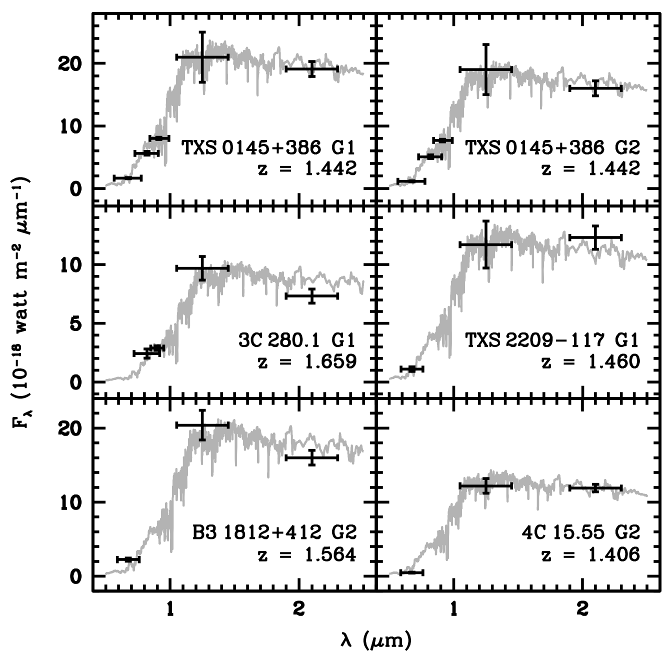

Figure 2. Examples of old galaxies found in fields of quasars at $z \sim 1.5$. Vertical bars show 1σ photometric errors; horizontal bars show filter FWHM. Gray traces are 4 Gyr Bruzual-Charlot (1996) models.

4. An Example: the Field of TXS 0145+386

Figure 3 shows the field of the $z = 1.446$ quasar TXS 0145+386, in bands ranging from R to J. Two EROs, G1 and G2, are marked, and their spectral-energy distributions are shown at the top of Fig. 2. We have obtained a spectrum of G1, unfortunately through cirrus, so the S/N is not sufficient to measure age-diagnostic spectral features. However, it does confirm a redshift of 1.4533 from a weak but broad [O II] λ3727 line, which possibly indicates the presence of a hidden active nucleus.

Figure 4 shows adaptive optics (AO) imaging of G1. With images having a FWHM of $0\farcs16$, the galaxy is seen to have a generally symmetric elliptical profile, with some faint irregular structure extending to the east. The other candidate (G2) is too far from the guide star for AO imaging, but its morphology on other images suggests that its structure is less regular (see Fig. 3), in spite of evidence

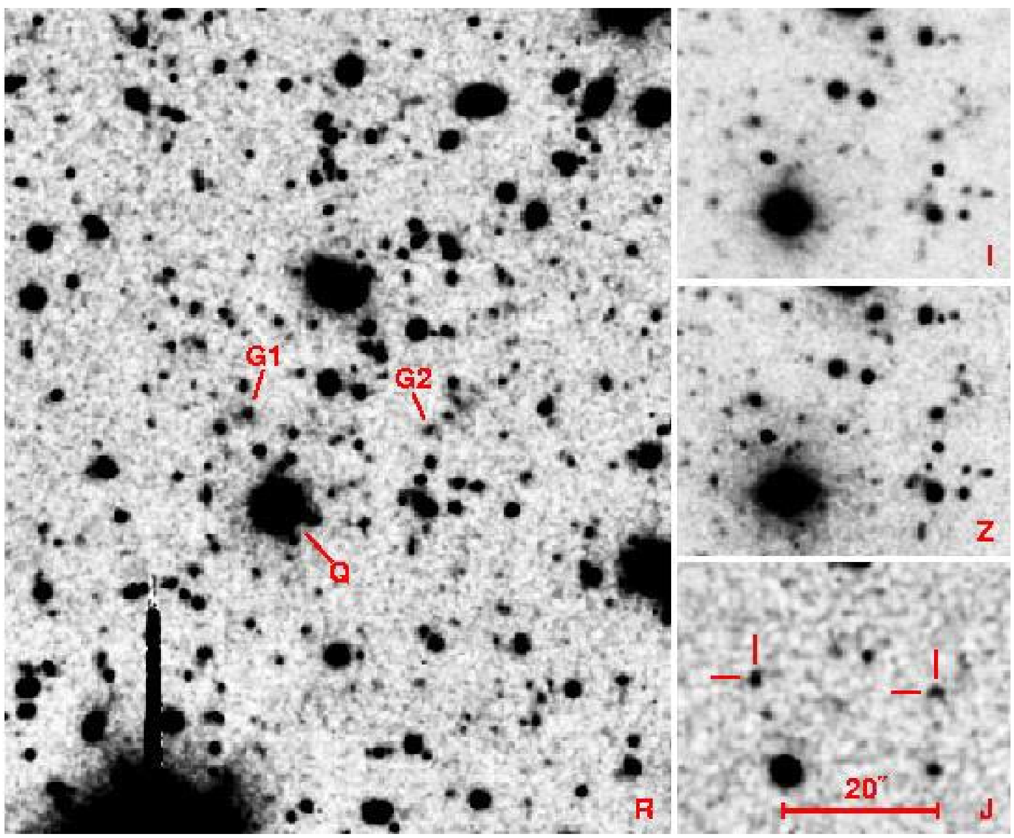

Figure 3. Images of the field of TXS 0145+386 in R, I, Z, and J bands. The R and Z images were obtained with LRIS on Keck II, and the I and J images were obtained with the UH 88-inch telescope. The quasar (Q) and the two red galaxies, G1 and G2 are marked. Note the evidence for a cluster of faint objects in the vicinity of the quasar and red galaxies.

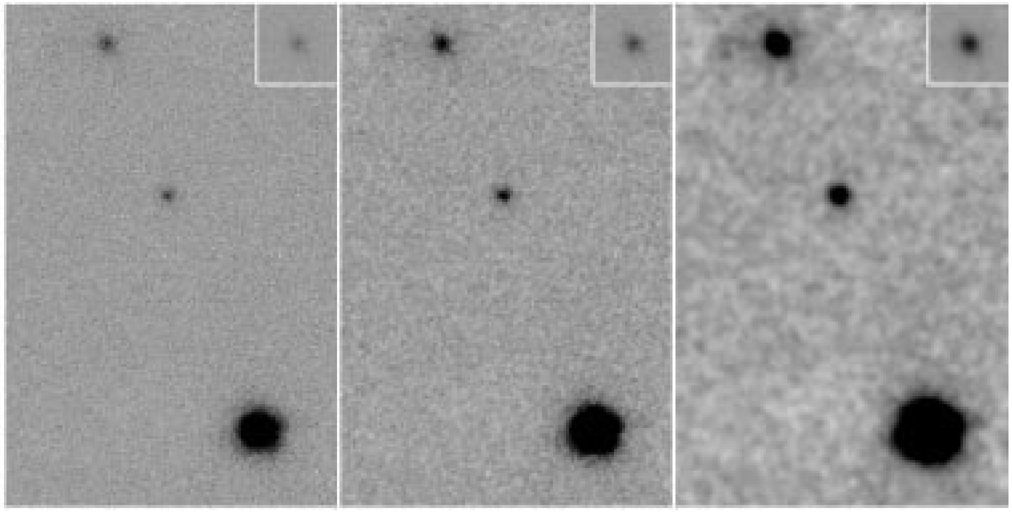

Figure 4. Adaptive optics imaging of the field of TXS 0145+386 at K', obtained with PUEO on the Canada-France-Hawaii telescope. The left panel shows the unsmoothed image, with FWHM = $0\farcs16$. The candidate old galaxy G1 is at the top, the nearly stellar object near the center is a compact galaxy with $z = 0.7883$, and the quasar itself is the bright object at the bottom. The center and right panels show the same image, smoothed with a Gaussian with $\sigma = 1$ and $\sigma = 3$ pixels, respectively. Insets show G1 at lower contrast. The structure seen to the east of G1 in the right panel appears in both nights' data. Panels are $10'' \times 15''$.

that its stellar population is as old as that of G1 (Fig. 2). Candidates in other fields also seem to show a variety of morphologies. The implication seems to be that, even with apparent stellar ages of 3–5 Gyrs, these galaxies may not all be completely relaxed systems in their outer parts, and we may be able actually to observe some aspects of the final stages of bulge formation.

There is an apparent concentration of very faint galaxies in the region around the quasar, G1, and G2, as seen in Fig. 3. Figure 5 gives another view of this clustering. It is often suggested that powerful radio sources can be used as markers to locate regions of high density at high redshifts. However, while strong radio sources are undoubtedly statistically in regions of higher density than is the average galaxy, there appears to be a large dispersion in the densities of radio source environments. Some seem to be in fairly rich clusters (Dickinson, Dey, & Spinrad 1995; Chapman, McCarthy, & Persson 2000), but some seem not to be (*e.g.,* Stockton & Ridgway 1997). It may well be that the presence of nearly fully formed galaxies comprising old stellar populations is a more reliable indicator of a rich cluster: under most plausible formation scenarios, processes of galaxy evolution will proceed more rapidly in strongly overdense regions. The identification of such galaxies in radio source fields may be one of the best ways of finding rich clusters at redshifts beyond the practical range of current wide-area X-ray surveys.

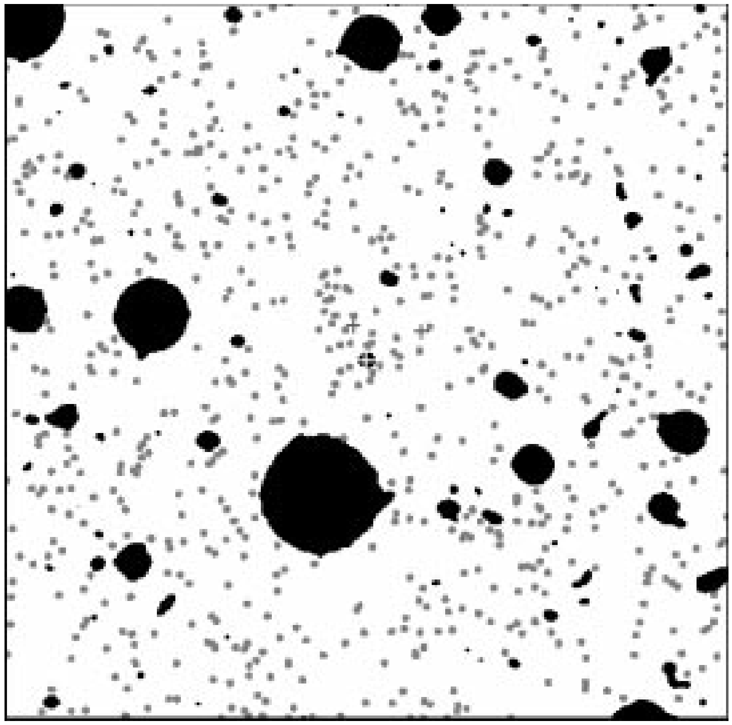

Figure 5. Clustering of galaxies with $24.5 < Z_{AB} < 26$ (gray dots) in the field of the quasar TXS 0145+386 (white cross on black object at center). The two red galaxies G1 and G2 are marked with gray crosses. Regions in black are obscured by bright stars or galaxies. The region shown is $4\overset{\prime}{.}3$ on a side.

5. Determining Ages of Stellar Populations

The main difficulty in attempting to use old galaxies at moderately high redshifts to constrain cosmological parameters is in establishing a robust age for the stellar population. Both we (Stockton, Kellogg, & Ridgway 1995) and Dunlop *et al.* (1996; see also Spinrad *et al.* 1997) have attempted to use spectroscopic age diagnostics. The spectral features of interest fall in the rest-frame near-UV (2600–3200 Å) and potentially give good age discriminants over the age range $\sim$ 1–5 Gyr. Figure 6 shows our preliminary reduction of a spectrum of one of two EROs in the field of the $z = 1.406$ quasar 4C15.55, which fairly closely matches a 3-Gyr-old model.

The major uncertainty in the results so far is in the reliability of the spectral synthesis models (*e.g.,* Bruzual & Magris 1997; Dunlop 1998, 2000; Heap *et al.* 1998; Yi *et al.* 2000; Nolan *et al.* 2001). However, as Dunlop (2000) has emphasized, much of this disagreement is due to the inclusion of broad-band colors in determining the ages; from the spectroscopic age diagnostics alone, the age dispersion is much smaller. In addition to being sensitive to reddening, ages from colors are especially dependent on getting rather uncertain late stages of stellar evolution right. On the other hand, while ages derived from restframe near-UV absorption features require more observing time, they have important

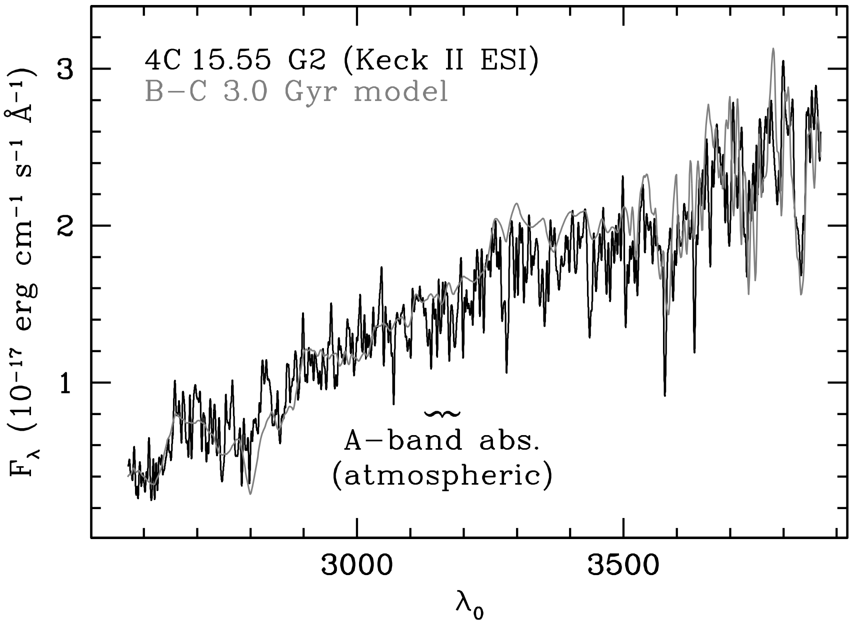

Figure 6. The spectrum of 4C15.55 G2 ($R = 26.6$), obtained with ESI on Keck II. The gray trace shows a Bruzual & Charlot (1996) 3 Gyr spectral synthesis model for comparison.

advantages: (1) they are potentially capable of higher precision and depend essentially only on the turnoff age of main-sequence F stars, where the models are on much firmer ground; (2) they are almost totally insensitive to the IMF of the stellar population; and (3) they are also insensitive to reddening. The most serious worry has been the age—metallicity degeneracy (*e.g.,* Worthy 1994), which can affect both colors and spectral features. However, recent work by Nolan *et al.* (2001) indicates that, with sufficiently good data, it is possible to break this degeneracy from the rest-frame near-UV spectroscopy alone. Thus, while it is still quite reasonable to *select* candidates on the basis of colors, it is essential to obtain spectroscopy in the rest-frame near-UV in order to determine robust lower limits to the age of the stellar population. In the meantime, models of increasing sophistication are being developed by several groups, and such refinements as incorporating α-enhanced stellar atmospheres and evolutionary tracks are likely to be available soon.

6. Higher Redshifts

In parallel with completing our survey for old galaxies in the fields of quasars with $z \sim 1.5$, we are extending the search to higher redshifts. Now that it seems clearly established that there are galaxies at $z \sim 1.5$ with ages of $\gtrsim 3$ Gyr, we are seeking to identify precursors to these objects at $z \sim 2.5$ with CISCO on the 8.2 m Subaru telescope. At this redshift, the oldest galaxies should be ~ 1.5 Gyr younger than at $z \sim 1.5$.

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Acknowledgments. I wish to acknowledge and thank my collaborators in these projects, Gabriela Canalizo, Susan Ridgway, Toshinori Maihara, and Bill Vacca. This work has been partially supported by NSF Grant AST95-29078. It has also made use of the NASA/IPAC Extragalactic Database (NED), which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under constract with the National Aeronautics and Space Administration. The observations described in this paper were obtained with the NASA Infrared Telescope Facility, the University of Hawaii 88-inch Telescope, the Canada-France-Hawaii Telescope, and the Keck Observatories, and I wish to express my gratitude to those who have provided these facilities and those who maintain and operate them.